# A NEW TEST OF THE EQUIVALENCE PRINCIPLE: AN UPDATE ON THE EOT-WASH EXPERIMENT

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## ABSTRACT

This report summarizes the results obtained by the Eot-Wash group at the University of Washington during the past year. Three topics are discussed: a new limit on the equivalence principle using Al and Be masses in the field of the earth, the status of an experiment that uses a massive rotating source, and a discussion of the implications of equivalence principle experiments using matter for the gravitational properties of antimatter.

## I. INTRODUCTION

There has been renewed interest in torsion balance experiments to detect a hypothesized intermediate ranged fifth force. Now that the weight of experimental evidence has fallen in disfavor of the existence of a new force, it is natural to ask what more can be learned from torsion balance experiments. Modern experiments with increased sensitivity can test more precisely the equivalence principle, upon which is based the general theory of relativity. More precise experiments can test the existence of new composition dependent interactions weaker than that originally proposed for the fifth force. In addition, a closer look at existing data can be used in a general field theoretic framework to set strong limits on an anomolous gravitational acceleration of antimatter. This report details the progress of our group on these three fronts during the past year.

## II. A NEW TEST OF THE EQUIVALENCE PRINCIPLE IN THE FIELD OF THE EARTH

At the 1990 Moriond Workshop[1], our group presented the results of a test of the equivalence principle for Be and Cu, and Be and Al test bodies falling in the field of the earth: $m_i/m_g(Cu) - m_i/m_g(Be) = (0.2 \pm 1.0) \times 10^{-11}$ and $m_i/m_g(Al) - m_i/m_g(Be) = (0.5 \pm 1.3) \times 10^{-11}$, where $m_i$ and $m_g$ are the inertial and gravitatational masses, respectively. A more complete description of this experiment has since been published elsewhere[2]. We have made improvements to the apparatus used in this work and have embarked on a new round of equivalence principle measurements.

To improve upon our previous results requires both a reduction of the measurement noise and a reduction of the dominant systematic errors. The experimental noise was due to both seismic disturbances, noticeably worse during the day than at night, and thermal fluctuations as the equilibrium torsional position of our $20 \mu m$ diameter W fiber is a sensitive thermometer. As seen in Table III of ref. 2, the dominant systematic errors in the previous work were excitations of the torsional mode of the pendulum caused by the rotation drive of the apparatus and the stability of the drive, quantifying the effects of thermal variations on the data, and spurious signals due to gradients in the ambient gravitational field. We have made substantial improvements to each of these problems, except for the seismic noise, and have taken new data with Be and Al test bodies.

The experimental apparatus is shown in Fig. 1. Four gold coated test bodies of equal mass and identical outside dimensions (two of Be and two of Al) form a composition dipole on a pendulum with vanishing mass quadrapole moment. The pendulum is suspended from a gold coated W wire inside of a vacuum vessel with a typical residual pressure of 1 torr. The torsional position of the pendulum with respect to the vacuum vessel (can) is monitored by an optical autocollimator using light reflected off of one of four identical mirrors mounted on the pendulum. The entire vacuum vessel is slowly rotated on a precision bearing at a rate such that the can revolution period is equal to eight torsional periods of the pendulum ($\tau_{torsional} = 714 sec$). The entire rotating system is contained inside of a cylindrical Cu thermal shield whose temperature is regulated by water from a constant temperature bath.

The signal of interest is a torque (or change in the torsional equilibrium position) that occurs at the can rotation ($1\omega_{can}$) frequency. The two components of this torque are referred to as $a_{cos\phi}$ and $a_{sin\phi}$ where $\phi$ is the angle of the can with respect to laboratory coordinates. An important systematic check is to reverse the composition dipole on the pendulum by physically moving the test bodies. We refer to these two orientations of test bodies as configurations A and B. The laboratory is located on a hillside to provide a source mass for interaction ranges of $\approx 1\ m$ to $10\ km$, while the centrifugal sling of the pendulum of $\approx 1.7\ mrad$ due to the earth's rotation allows the earth to be the source mass for ranges greater than the earth's radius.

The dotted line labelled 14 in Fig. 1 is an additional, rotating thermal shield that has been added to passively reduce thermal variations of the torsional fiber. In our previous work without this additional shield, a modulation of the temperature of the outer Cu thermal shield by $\pm 0.9\ K$ at the can rotation frequency gave rise to a 14.4 $\mu rad$ torque on the pendulum at $1\omega_{can}$. With the new passive shield installed, the same $\pm 0.9\ K$ modulation resulted in a torque at $1\omega_{can}$ of only 1.4 $\mu rad$, a tenfold improvement in thermal isolation.

The rotation drive of the apparatus is controlled by a crystal oscillator whose output is divided down to drive a micro-stepped stepping motor. Variations in the can rotation frequency due to imperfections in the gear of the bearing can excite the torsonal mode of the pendulum and give rise to spurious signals at $1\omega_{can}$. We now employ a 900,000 pulse per revolution rotary encoder to measure the can rotation speed and we feed back a signal to the stepping motor to hold the speed constant. Fig. 2 shows the output of the autocollimator for one can revolution (averaged over many revolutions) for our previous data before we used the feedback, and for our new data with the feedback in operation. Without the feedback, a 14.3 $\mu rad$ coherent torsional amplitude was induced by speed irregularities, while with the feedack in operation we now measure a coherent torsional excitation of 1.3 $\mu rad$, again a tenfold improvement.

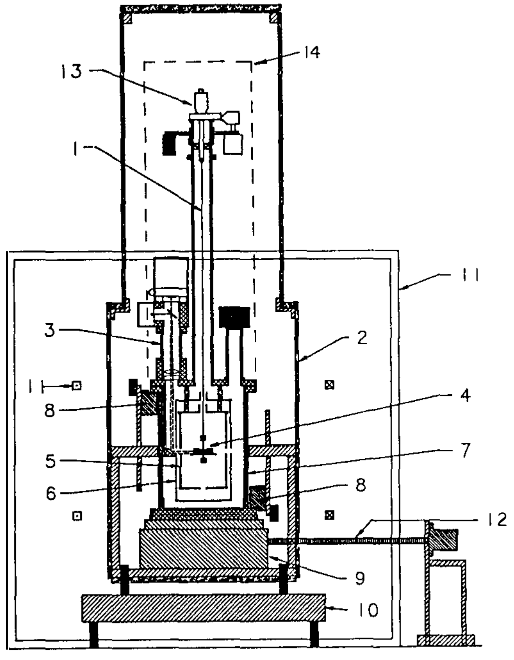


Figure 1. Side view of the torsion balance apparatus. 1) W fiber 2) thermal shield 3) autocollimator 4) torsion pendulum 5,6) magnetic shields 7) vacuum vessel and magnetic shield 8) gravity gradient compensator 9) turntable 10) baseplate 11) Helmholtz coils 12) turntable drive shaft 13) fiber positioner 14) inner thermal shield

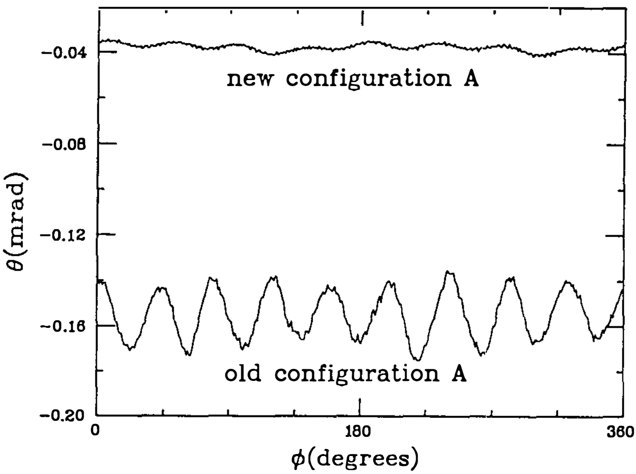


Figure 2. The autocollimator signal versus the orientation, $\phi$, of the rotating vacuum can with respect to the lab, averaged over many revolutions. $\theta$ is the rotation angle of the torsion balance relative to the vacuum can. The torsional oscillations that are observed come from a non-constant can rotation rate.

The gravity gradient compensator labelled 8 in Fig 1 is used to cancel the gradient of the gravitational field at the site of the apparatus (due primarily to the local hillside) without inducing substantial higher derivatives in the gravitational potential. By using special test bodies whose centers of masses are displaced from their geometrical centers, we determined that the compensator in our previous work canceled the local gradient to one part in 145. We have improved the compensator to now cancel the local gradient to one part in 400.

These improvements to the apparatus along with the auxilliary measurements described in ref. 2 to test for systematic errors have reduced the total systematic error of the new results to less than 3 *nrad*. Our new results are summarized in Table 1 and are compared to our previous (1989) results. The rows labelled $(A-B)/2$ are the difference between the observed $1\omega_{can}$ signals for the test bodies in the $A$ and $B$ configurations and represents a composition dependent torque. The rows labelled $(A+B)/2$ are the average of the two configurations and represents the $1\omega_{can}$ torques that are due to imperfections in the apparatus. Taking the south component of the measured composition dependent torque, we conclude that

$$m_i/m_g(Al) - m_i/m_g(Be) = (0.1 \pm 0.8) \times 10^{-11}$$

| Signal | 1990 | 1989 |
|---|---|---|
| $\frac{1}{2}(A-B)$ | $a_{cos\phi} = -7 \pm 17\ nrad$<br>$a_{sin\phi} = +7 \pm 17\ nrad$ | $a_{cos\phi} = -21 \pm 26\ nrad$<br>$a_{sin\phi} = -17 \pm 27\ nrad$ |
| $\frac{1}{2}(A+B)$ | $a_{cos\phi} = 39 \pm 17\ nrad$<br>$a_{sin\phi} = 0 \pm 17\ nrad$ | $a_{cos\phi} = +76 \pm 26\ nrad$<br>$a_{sin\phi} = 142 \pm 27\ nrad$ |

Table 1: Comparison of our new results (1990) with our previous results (1989)

Combining our new result with our previous result, we find a new limit for the equivalence between the inertial and gravitational masses of Al and Be test bodies in the field of the earth to be $(2.3 \pm 6.9) \times 10^{-12}$. This new result should be considered preliminary because additional data are still being acquired.

## III. MASSIVE LOCAL SOURCE EXPERIMENT

There are two important motivations and several experimental benefits that come from using a laboratory source mass in torsion balance experiments. To search for a composition dependent interaction using the earth as a source necessarily leaves one insensitive to an interaction for which the charge of the earth vanishes. In addition, the shortest range that can be probed is limited by how close the apparatus can be positioned relative to the earth. Both of these limitations are overcome by using a compact dense laboratory source mass, positioned very near to the torsion balance. If the source mass position is modulated, a stationary, vibration isolated torsion balance operated under high vacuum can be employed which may greatly increase the signal to noise ratio compared to the rotating torsion balance performance described in section II. Our group is building a rotating source apparatus to search for composition dependent interactions with ranges as small as 2 *cm*. This technique has already provided important results to other groups[2-5].

The rotating source apparatus is shown in Fig. 3. A 2900 *kg* depleted U source mass rests on a rotating platform and is counter balanced by a Pb mass at a longer moment arm. The U is split into an upper and lower half. Each half has the shape of a half ring with inner radius 10 *cm* from the center of the torsion balance. The symmetry and dimensions of the U mass ensure that the $Y_{lm}$ moments of its gravitational potential for even $l$, any $m > 1$, and $l = 3, m = 1$ vanish at the center of the torsion balance. Opposite

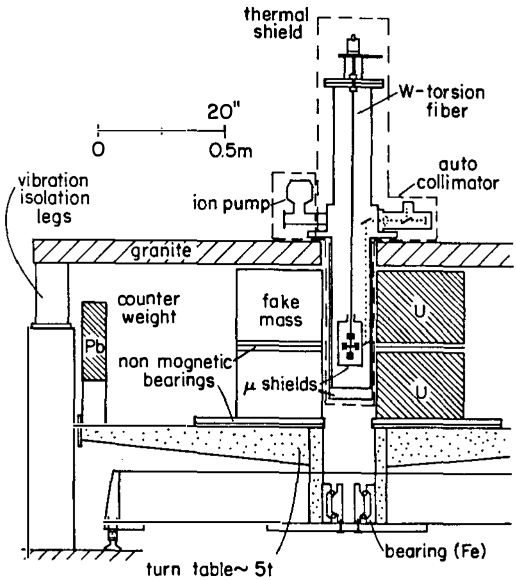


Figure 3. Design of a rotating source apparatus that allows 2900 *kg* of depleted uranium to be smoothly rotated around a stationary torsion balance.

the U masses will be hollow Al fake masses that complete the enclosure around the torsion balance vacuum vessel. The upper and lower halves of the U can be rotated relative to one another to alter the gravitational gradients from the U. The entire source mass will be rotated at a constant rate, most likely at the resonant frequency of the torsion balance.

A highly symmetric torsion balance using four masses arranged in a composition dipole configuration will be suspended from a Au coated W fiber inside a high vacuum chamber. Initially, Cu and Pb test bodies will be used which along with the U source give good sensitivity to a force whose charge is proportional to isospin. The balance is located within a Au coated magnetic shield, and a second magnetic shield as well as a Cu thermal shield surrounds the lower half of the vacuum vessel. The balance is supported on a granite table which in turn rests on three air pad vibration isolation legs. The air pressure in the pads is servoed to prevent the granite table from tilting[6]. The air pads provide 20 *db* of attenuation at the 7 *Hz* bounce mode frequency of the pendulum which we find is the dominant mode for coupling seismic noise into the torsional mode.

With reduced seismic noise and an increased $Q$ of the pendulum coming from a vacuum of $10^{-6}$ torr, we anticipate an increase in signal to noise of at least 30 compared to our rotating balance experiment described in section II. The improved experimental sensitivity along with the massive local source should allow us to search for composition dependent interactions at new levels of precision and for ranges as small as $\approx 2$ *cm*.

## IV. DO MATTER AND ANTIMATTER FALL WITH THE SAME ACCELERATION?

There has been much interest at previous Moriond workshops concerning the gravitational properties of antimatter. According to general relativity, matter and antimatter should have identical accelerations in a gravitational field. Attempts to build a quantum theory of gravity, however, often lead to scalar and vector partners of the familiar spin 2 graviton, which can lead to different gravitational accelerations for matter and antimatter[7,8]. Our group has recently argued[9] that within the framework of ordinary field theories, equivalence principle tests and tests of the inverse square law of gravity using ordinary matter set stringent limits on the anomalous acceleration of antimatter. This argument will be outlined briefly below.

In standard field theories, the exchange of even spin bosons lead to attractive forces between unpolarized bodies, while the exchange of odd spin bosons gives rise to a repulsive force between like bodies and an attractive force between bodies of opposite charge. Hence any difference between the gravitational acceleration of matter and antimatter must be due to an odd spin boson (such as a vector interaction which is the case we consider). Restricting our attention to first generation fermions, there are three independent vector charges which we can label $q_e$, $q_p$, and $q_n$ for the electron, proton and neutron (with opposite sign for the corresponding antiparticle). The linear combination $q_p - q_e$ is proportional to electric charge which would make the new vector interaction indistinguishable from the ordinary electric forces (for ranges larger than the scale of the experimental apparatus). Laboratory based experiments with matter and antimatter are therefore both sensitive to only $q_e + q_p$ and $q_n$.

Different materials have varying $q_e + q_p$ and $q_n$ charge to mass ratios due to the variations in the neutron to proton ratio and nuclear binding energies. The null results from equivalence principle measurements set limits better than $10^{-3}$ $cm/sec^2$ for the acceleration of antimatter at the earth's surface due to a vector interaction that couples to these charges.

Could the repulsive gravi-vector force in equivalence principle experiments be cancelled by an attractive gravi-scalar force? If only one pair of test bodies had been measured, the answer would be an unlikely yes. However, more than five different pairs of test bodies have given null results in equivalence principle experiments. The different inherent nature of scalar and vector charges (different Lorentz transformation properties and different contributions from binding energy, for example) makes these charges vary differently for different materials, so that exact cancellation of a scalar and vector force cannot occur for all materials.

We have considered in detail three scalar charges to see to what extent the forces associated with them might cancel the vector interaction in equivalence principle experiments. Taking the scalar charges $q_s = m$, $q_s = m + 0.01B$, and $q_s = B + 10^{-6}B^2$ and the vector charge $q_v = B$ in each case, where $m$ is the mass and $B$ is the baryon number of the test body, we find that in each case, combinations of equivalence principle measurements and tests of the inverse square law of gravity limit the anomalous acceleration of antimatter at the earth's surface to be less than $10^{-3}$ $cm/sec^2$. We conclude that experiments using ordinary matter provide a direct test for the presence of scalar and vector partners to the graviton, and that there is no evidence for such partners at a level below $10^{-6}$ times the strength of ordinary gravity.

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